OFFICE OF NAVAL RESEARCH

Grant N00014-90-J-1193

TECHNICAL REPORT No. 18

Specific Heat of Anisotropic Superconductors

by

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Prepared for Publication

in

Quarterly Report of the New York Institute on Superconductivity
Volume 3, Number 1, Summer 1990

Departments of Chemistry and Physics
State University of New York at Buffalo
Buffalo, New York 14260

July 1990

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): UBUFFALO/DC/90/TR-18	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION: Depts. Chemistry & Physics, State University of New York; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code): Fronczak Hall, Amherst Campus, Buffalo, New York 14260	7b. ADDRESS (City, State, and ZIP Code): Chemistry Program, 800 N. Quincy Street, Arlington, Virginia 22217
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Office of Naval Research; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Grant N00014-90-J-1193
8c. ADDRESS (City, State, and ZIP Code): Chemistry Program, 800 N. Quincy Street, Arlington, Virginia 22217	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Specific Heat of Anisotropic Superconductors

12. PERSONAL AUTHOR(S)
D. Sahu, A. Langner and Thoma ". George

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ____ TO ____	July 1990	5

16. SUPPLEMENTARY NOTATION
Quarterly Report of the New York State Institute on Superconductivity
Volume 3, Number 1, Summer 1990

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
ANISOTROPIC SUPERCONDUCTORS, FERMI SURFACE, SPECIFIC HEAT, DEBYE ENERGY, ENERGY GAP, MATSUBARA FREQUENCY

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A theoretical approach for obtaining a Ginzburg-Landau free-energy expansion for a class of even-parity superconducting states that enables the calculation of thermodynamic quantities for heavy-fermion and other conventional superconductors is discussed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr. David L. Nelson	22b. TELEPHONE (Include Area Code): (202) 696-4410; 22c. OFFICE SYMBOL

DD Form 1473, JUN 86 — Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

Quarterly Report, Volume 3, Number 1, Summer 1990
New York State Institute on Superconductivity

SPECIFIC HEAT OF ANISOTROPIC SUPERCONDUCTORS

by

D. Sahu, A. Langner and Thomas F. George

Thermodynamic properties of superconductors provide valuable information about the nature of the superconducting state. The existence of an energy gap Δ in isotropic superconductors leads to an exponential dependence of specific heat on the gap function: $C_s \propto \exp(-\Delta/k_B T)$, where k_B is Boltzmann's constant and T is the absolute temperature. For anisotropic superconductors, the energy gap function Δ vanishes along lines or planes of the Fermi surface leading to a power law dependence of specific heat on the temperature. The temperature dependence of specific heat thus leads one to draw conclusions about the nature of the excitation spectrum.

It has been realized in recent years that in "heavy-fermion" superconductors,[1] electron pairing could arise due to a p-wave state or a d-wave state. For a p-wave state, the relative orbital angular momentum of the pair, ℓ, is equal to 1 and the spins form a tiplet state. On the other hand, for a d-wave state the relative orbital angular momentum of the pair is given by $\ell = 2$ and the spins form a singlet state. Calculation of the specific heat for these anisotropic superconductors can be done analogous to Bardeen-Cooper-Schrieffer (BCS) superconductors from the free energy expansion. In the imaginary time representation, the free energy difference, F_n-F_s, between the normal state and the superconducting state for a BCS superconductor is[2]

$$F_n - F_s = N(0) \left\{ -\Delta^2 ln(t) + 4\pi T \sum_{n=0}^{n_D} [(|\Delta|^2 + \omega_n^2)^{1/2} - \omega_n - |\Delta|^2 (2\omega_n)^{-1} \right\} ,$$

where N(0) is the density of states per single spin evaluated at the Fermi surface, t is the reduced temperature, $\omega_n = \pi T(2n+1)$ is the Matsubara frequency, and n is an integer with an upper limit of n_D corresponding to the Debye cutoff frequency. The entropy S and the specific heat C_s are related to the free energy through $S = -(dF/dT)$ and $C_s = T(dS/dT)$. In carrying out the differentiation, one has to bear in mind that both Δ and ω_n depend on temperature.

The BCS theory is based on a simple intuitive model for the effective attractive interaction between electrons, namely that the interaction potential is attractive for wave vectors **k** that lie within a small spread of $\pm \Delta_k$ around the Fermi wave vector k_F and that the potential is ≥ 0 otherwise. In addition, the Debye energy ω_D is assumed to be much larger than the energy ξ_k of the electrons. This approximation is called the "weak-coupling" limit, and many superconductors fall into this category. However, there are superconductors for which the electron-phonon coupling is strong, requiring the BCS theory to be modified. This is done in the "strong-coupling" theory of Eliashberg, which utilizes the fact that the electron-phonon interaction is not instantaneous, but rather is delayed in time (retardation). For details of this theory we refer the reader to the book by Mahan.[3] Other applications and extensions of the BCS ideas can be found in the excellent two-volume set edited by R. D. Parks.[4] It should be mentioned here that a strong-coupling, phonon-mediated model has been proposed to explain the properties of the new "high-T_c" superconductors.[5] However, this model deviates from BCS theory in that the primary charge carriers are bosons (integral spin) rather than fermions.

The present authors have developed a systematic analysis to obtain a Ginzburg-Landau free-energy expansion for a class of even-parity superconducting states[6,7] that enables the calculations of thermodynamic quantities for the heavy-fermion and other conventional superconductors. A preliminary application of this approach to model the effect of anisotropy in the new "high-temperature" superconductors has also been pursued with some measure of success.[8] The main ideas in the above works are: (1) the superconducting states can be anisotropic consistent with the symmetry of the underlying lattice and (2) the anisotropic states can couple to other anisotropic or isotropic states that are permitted by group theory. The construction of these generalized free energies follows the usual prescription of combined operations of rotational invariance, time reversal invariance and gauge invariance. The Matsubara imaginary time representation then provides a convenient tool for carrying out the analytical calculation of the thermodynamic quantities. This tool is again very convenient to handle complex situations, such as evaluation of position-dependent energy gaps that occur when a bulk superconductor is in contact with a thin film of a normal metal (a proximity function) or in situations in which an external current is passed through such a junction.

The work of the authors described above was supported by the Office of Naval Research and an award from the New York State Institute on Superconductivity in conjunction with the New York State Energy Research and Development Authority.

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